water

MDPI

Article

Simulating the Effects of Agricultural Management on Water Quality Dynamics in Rice Paddies for Sustainable Rice Production—Model Development and Validation

Soon-Kun Choi [1], Jaehak Jeong [2] and Min-Kyeong Kim [1,*]

1 Department of Agricultural Environment, National Academy of Agricultural Science, Wanju 55365, Korea; soonkun@korea.kr

2 Texas A&M AgriLife Research, Texas A&M University, 720 East Blackland Road, Temple, TX 76502, USA; jjeong@brc.tamus.edu

* Correspondence: kimmk72@korea.kr; Tel.: +82-63-238-1122

Received: 12 October 2017; Accepted: 30 October 2017; Published: 8 November 2017

Abstract: The Agricultural Policy/Environmental eXtender (APEX) model is widely used for evaluating agricultural conservation efforts and their effects on soil and water. A key component of APEX application in Korea is simulating the water quality impacts of rice paddies because rice agriculture claims the largest cropland area in the country. In this study, a computational module called APEX-Paddy (National Academy of Agricultural Sciences, Wanju, Korea) is developed to simulate water quality with considering pertinent paddy management practices, such as puddling and flood irrigation management. Data collected at two experimental paddy sites in Korea were used to calibrate and validate the model. Results indicate that APEX-Paddy performs well in predicting runoff discharge rate and nitrogen yield while the original APEX highly overestimates runoff rates and nitrogen yields on large storm events. With APEX-Paddy, simulated and observed flow and mineral nitrogen yield (QN) are found to be highly correlated after calibration (Nash & Sutcliffe Efficiency (*NSE*) = 0.87 and Percent Bias (*PBIAS*) = −14.6% for flow; *NSE* = 0.68 and *PBIAS* = 2.1% for QN). Consequently, the APEX-Paddy showed a greater accuracy in flow and QN prediction than the original APEX modeling practice using the SCS-CN (Soil Conservation Service-Curve Number) method.

Keywords: APEX; rice paddy; water quality; agriculture; modeling; nonpoint source pollution

---

1. Introduction

Rice is traditionally the most preferred grain crop in Korea. Even though the preference for rice has noticeably diminished recently with industrialization and the introduction of the western diet, rice remains as the predominant grain crop of the country. The total area of paddy fields in Korea is estimated to be 55% of the cultivated lands, claiming over one million hectares [1,2]. Rice cultivation starts in the spring season with the transplantation of rice seedlings and continues through the fall season. Paddies are kept flooded during most of the growing season (spring through summer) with intensive irrigation, fertilization, and weeding. Seasonally, about 25 to 50% of the annual rainfall occurs during the monsoon season (June and July) in Korea. Because the growing season for rice includes the monsoon period, the paddy fields are vulnerable to discharging sediment, nutrients, and other chemicals to downstream water bodies.

Rice production practices (e.g., improper application of chemicals, over-pumping of groundwater, and loss of biodiversity in rice paddies) are linked to water contamination, excessive salinity, and other environmental problems [3]. Intense fertilization during the rice cultivation period, especially in early season (May to June), may incur a high nutrient concentration in the effluent water discharged from paddies, causing an impairment of stream water quality [4,5]. Research has found that rice paddies are often the critical sources of environmental loadings that are discharged to the downstream water body in areas where rice paddies are a predominant land use [6,7]. On the other hand, rice paddies could provide ecosystem benefits by filtering nutrients and other chemicals through proper field management [1]. Matsuno et al. [8] suggest that an optimal paddy management including fertilizer application, discharge water reuse, and plot-to-plot irrigation can significantly reduce water quality problems. For example, Song et al. [5] found that a proper fertilizer application and control of outlet weir height could reduce the total nitrogen (TN) and total phosphorus (TP) discharge by 29 and 37%, respectively.

Computer models can simulate the different aspects of rice cultivation such as phenological stages, water management, and/or environmental impacts of rice production. Some models focus on simulating rice crop growth and yield, while taking into account various aspects of water, nutrient, and associated biophysical processes [9,10]. Other models are designed to simulate hydrologic balance, pesticide fate and transport, or the transport of other pollutants within rice paddies [11–13]. Applications of these models have focused heavily on single rice paddies or clusters of rice paddies within relatively small areas, although some models have been extended to support watershed-scale applications [14]. However, the comprehensive assessment of paddy water quality dynamics based on cropping systems simulation has been limited because few models are capable of simulating the effects of paddy management on bio-physical processes in an integrated modeling framework at the field-to-watershed-scale [15].

The Agricultural Policy/Environmental eXtender (APEX) model [16] was developed for use in whole farm/small watershed management and Best Management Practices (BMP) implementation [17]. Because of its comprehensive land management simulation, there is growing interest for APEX application among scientists and modelers in rice-growing Asian countries. However, the APEX model does not simulate paddy-specific practices such as puddling, flood irrigation management, or transplanting, making it difficult to apply the model to rice paddy dominant agricultural watersheds that are common to Korea. Therefore, a paddy simulation module is needed within APEX that enhances water quality simulation in rice paddy farms based on algorithms that connect paddy practices, rice growth, and water quality processes at the field-to-watershed scale.

The objectives of this study are: (1) to construct a physically-based modeling framework for simulating paddy processes by linking agricultural management practices including puddling, flood irrigation, transplanting, fertilizer application on flooded paddies, and irrigation management to rice growth and water quality dynamics within the APEX model; (2) to develop crop parameters that represent the growth characteristics of paddy rice; and, (3) to evaluate the paddy module using field data at two experimental paddy fields in Korea. The ability to account for differences in cultural practices, water dynamics, and pollutant cycling/transport among major types of rice production systems is an important attribute of the enhanced APEX-paddy module. Two experimental fields in the Icheon and Gimje regions in Korea were selected to test the performance of the paddy module.

2. Materials and Methods

2.1. Description of Study Site

Two experimental paddy fields operated by the National Institute of Agricultural Science were selected for case study areas as these paddy fields are rich in monitoring data, such as water balance, management records, weather data, and yield amounts [18,19]. The Icheon site is located in Gyeonggi-do province and the Gimje site is in Jeollabuk-do province. The Icheon (37°18′20.34′′ N, 127°30′40.46′′ E) and Gimje (35°44′56.13′′ N, 126°51′50.21′′ E) sites are both irrigated paddy fields representing interior and costal characteristics of the paddy environment for rice production in Korea (*Oryza sativa* L.) with cultivation areas of 15 and 0.5 ha, respectively (Figure 1). The majority of excessive water irrigated to paddy fields discharges into drainage canals. The two sites' landscapes are commonly defined by alluvial plains with poor soil drainage. The predominant soils are Seogcheon series at the Icheon site and Jeonbug series at the Gimje site. The topsoil of Seogcheon series is coarse loamy, which is somewhat poorly drained. The Jeonbug series is poorly drained silty soil built on the fluvio-marine plain. The average annual temperature is 12.8 °C and the average annual rainfall is 1024 mm. Seasonally, rainfall at the study sites is highly influenced by monsoon, a rainy season during the months of July and August in Korea. Approximately 45% of the annual rainfall occurs in the study area during this time. Because the growing season for rice in part includes the monsoon period, paddy fields are vulnerable to discharging sediment and nutrients to downstream water bodies.

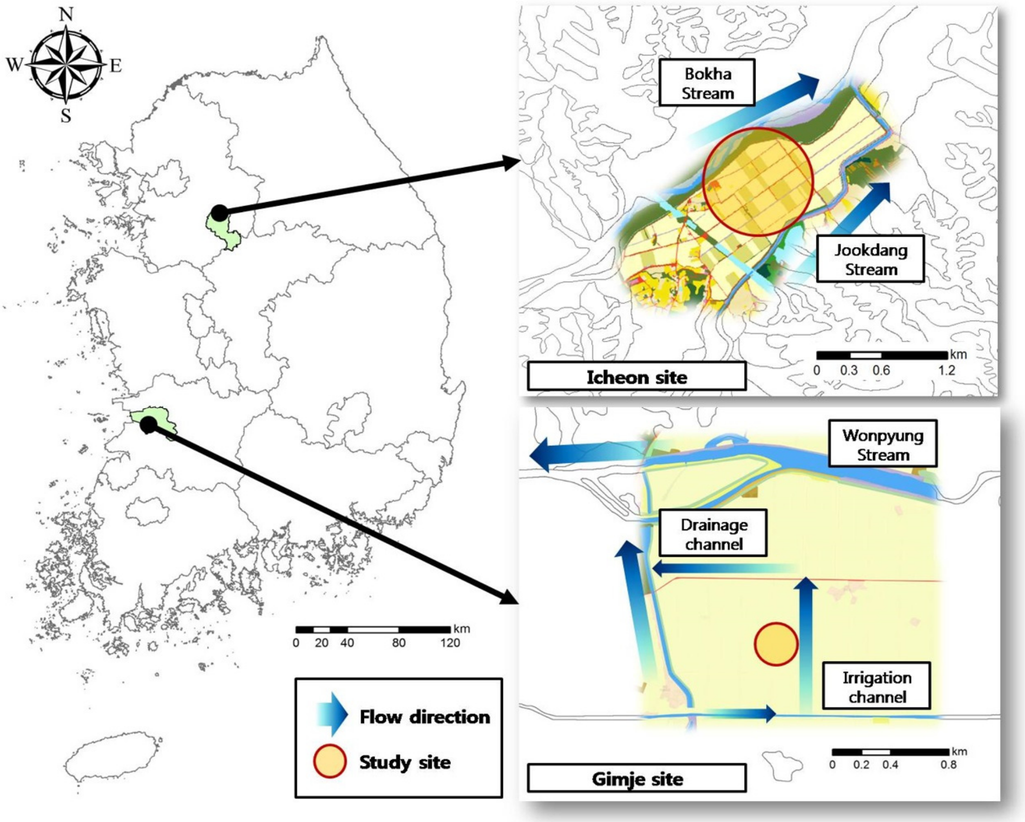

Figure 1. Topographical maps of the study areas. The Icheon site is located in province of Gyeonggi, and the Gimje site is located in the province of Jeonbug, Korea.

Rice is seeded and grown in nursery beds for 25–30 days and then transplanted after 1.5–2 leaves emerge. Transplanting is the most popular method of rice cultivation, and is undertaken in the paddy fields between mid-May and mid-June. The period of land preparation (i.e., puddling) and transplanting occur from May to August, during which water demand reaches the peak rate. In paddy cultivation, paddy fields are irrigated sufficiently to maintain water ponding. The depth of ponding water is managed at various levels between 5 and 10 cm during the growing season to control weeds and to maximize rice yield. Typically, the rice is harvested in October. Continuous monitoring of irrigation and surface discharge water at the paddy field were conducted from May to September in 2002 and 2003 in the Icheon area, and from May to September in 2014, at the Gimje site, for the purpose of quantifying and qualifying water and nutrients.

2.2. APEX-Paddy Model

APEX is a watershed model for simulating the impact of agricultural managements to water balance, nutrient cycling, carbon dynamics in soil-plant systems that runs on a daily time step [16,20].

APEX defines land areas with unique soil property, vegetation or land use, and the land slope as subareas. Therefore, a watershed is delineated into a system of subareas that are hydrologically connected by a stream network.

In this work a set of subroutines was developed and coded into the current APEX (version 1501) (Texas A&M AgriLife Research, Temple, TX, USA, https://epicapex.tamu.edu/apex/) to assess the impact of paddy management practices on rice growth, water balance, and water quality. This paddy sub-model is named APEX-Paddy. The greatest challenge in implementing APEX for paddy simulation lies in the fact that APEX Subareas are not coded to permit ponding conditions by flooding water. Therefore, the subarea module in APEX was enhanced to accommodate water ponding conditions with diking and outlet controls. Puddling is a tillage operation with shallow ponding water (saturating the soil is) in a paddy field. The top soil layer in the paddy becomes soft and suitable for transplanting rice seedlings after the puddling.

The standard spacing of rice in Korea is 14 cm × 30 cm. Thus, 23.8 plants per square meters are planted with three to four seedlings per plant. As rice grows after transplanting, the paddy rice goes into tillering as the fourth leaf is fully emerged. Tillers emerging from nodes in the main culm have the potential to produce panicles. APEX's crop growth module does not simulate tillering for rice. In crops such as rice, wheat and sugarcane that produce higher numbers of yielding tillers compared to the number of seeds or shoots planted, the plant population must be estimated based on the number of tillers producing the final yield. We used the following steps to calculate the rice population in the APEX model. According to the Korea Crop Test Report [21], the average effective tillering is 18.4. Assuming 3.5 seedlings per plant, the population increment per plant is 5.26, giving the final value of 125 (23.8 plants/m^2 × 5.26 tillers/plants). Consequently, transplanting of rice seedling is simulated with the plant population of 125 plants/m^2 in the APEX-Paddy model (http://www.naas.go.k). Prolonged soil saturation does not inhibit the growth of the roots of paddy rice like other aquatic plants. Typical paddy management schedule is summarized in Table 1. APEX-Paddy contains physically based algorithms to mechanically simulate these paddy operations and their effects on rice growth and nutrient cycling.

Table 1. Typical paddy management schedule of the Icheon field.

Date	Operation	Amounts
1 May	Pesticide application	30 kg/ha
5 May	Fertilizer application	61 kg N/ha, 42 kg P/ha
5 May	Ploughing	100 mm depth
10 May	Irrigate	100 mm ponding
15 May	Puddling	80 mm depth
19 May	lower water depth	25 mm ponding
20 May	Transplanting	125 stalks/ha
20 May	Irrigate	60 mm ponding
30 May	Pesticide application	30 kg/ha
10 June	Fertilizer application	24.2 kg N/ha
20 July	Stop irrigation and drain water	
25 July	Fertilizer application	12.1 kg N/ha
1 August	Irrigate	80 mm ponding
20 September	Stop irrigation and drain water	
30 September	Harvest	

The schematic of the APEX processes with the paddy module is illustrated in Figure 2. With the paddy enhancement, a subarea is flexible for setting land as dry or wet (flooded) as prescribed in the operation schedule file that is attached to the subarea. APEX estimates surface runoff discharge and infiltration using the SCS-CN method [22], and soil erosion is estimated by the USLE (Universal Soil Loss Equation) equation [23] or other variations of the USLE. Daily actual evapotranspiration (AET) is calculated as the sum of plant transpiration and soil evaporation, which is equal or less than the estimated daily potential evapotranspiration (PET). APEX-paddy provides a set of new subroutines to simulate water ponding, discharge control, AET possibly greater than PET under wet condition, and paddy managements. During the rice period, the development of leaf areas promotes a greater transpiration while reducing the exposure of the soil surface to the incoming solar radiation. Daily AET values of rice paddy can often exceed the estimated daily PET during the mid-season after the canopy is established due to high solar radiation, wind speed, and root water uptake. Vu et al. [24] found AET values up to 50% greater than PET values during mid-seasons depending on varieties and regional conditions. When a subarea is set to simulate paddy rice management, APEX-Paddy switches from the SCS-CN method to a weir discharge function to control water balance in the paddy. Sediment yield is estimated based on the settling rate after puddling and then residual sediment concentration in the ponding water. Daily AET may exceed PET during the summer season after rice establishes a full canopy. Infiltration of ponding water occurs continuously based on the saturated hydraulic conductivity of the top soil layer. During off-seasons or when paddy field management does not implement water ponding, APEX-Paddy switches back to default subarea modules to simulate upland non-ponding land processes, such as the SCS-CN method for runoff estimation. A puddling operation results in a rapid resuspension of sediment and nutrient, thus making sediment and nutrient concentration high in the ponding water before the suspended solids resettle. Growth characteristics of paddy rice were developed and calibrated based on field measurement data at the Suwon site in Gyeonggi-do. Leaf area index, dry weight and root weight ratio were measured.

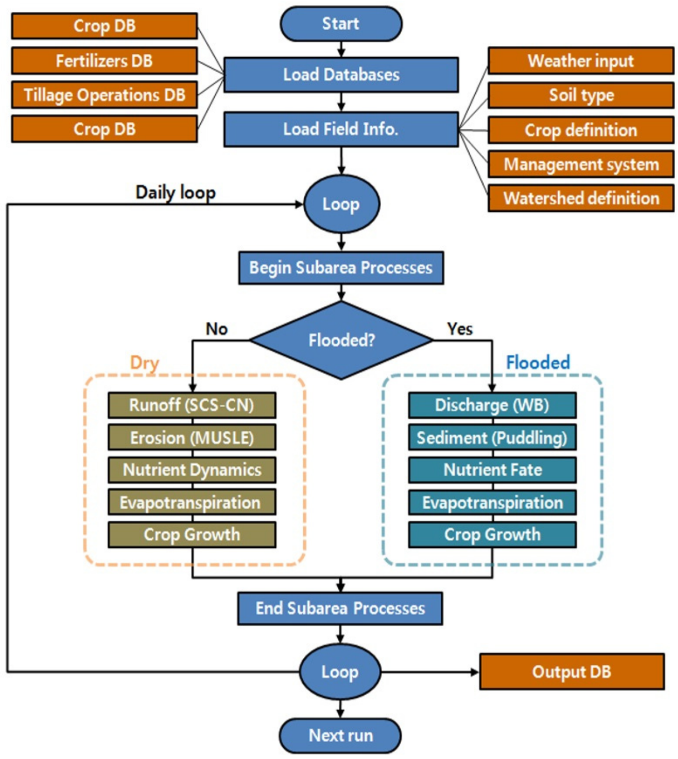

Figure 2. Schematic diagram of the Agricultural Policy/Environmental eXtender(APEX)-Paddy algorithm.

2.2.1. Evapotranspiration

The APEX-Paddy model uses the equations of Penman-Monteith [25] and Stockle et al. [26] for calculating plant transpiration. For paddy simulation, the actual daily evapotranspiration method as suggested by Sakaguchi's [27], is incorporated to represent crop coverage and flood condition.

The amount of evaporation and plant transpiration from the soil and the leaf surface are calculated using following equations:

$$\lambda E_0 = \frac{\Delta R_n + 86.66\rho_a \, VPD \, u_{10}/350}{\Delta + \gamma} \tag{1}$$

$$EP = \frac{\Delta R_n + 86.66\rho_a \, VPD/r_a}{\lambda\left[\Delta + \gamma\left(1 + \frac{r_c}{r_a}\right)\right]} \tag{2}$$

where, λ is the latent heat of vaporization (MJ(Mega Joule)/kg), E_0 is daily potential evapotranspiration (mm/d) for the reference crop, alfalfa with a 40 cm height, EP is daily crop transpiration (mm/d), Δ represents the slope of the saturation vapor pressure temperature relationship (kPa/°C), and R_n is net solar radiation (MJ/m^2/d). ρ_a is the mean air density at constant pressure (kg/m^3), VPD represents the vapor pressure deficit of the air (kPa), u_{10} is daily mean wind speed from a point 10 m above the ground, is the psychrometric constant (kPa/°C), r_c is the plant canopy resistance (s/m), and r_a is the diffusion resistance of the air layer (s/m). Canopy resistance is estimated by dividing the minimum surface resistance for a single leaf by one-half of the canopy leaf area index [28]. The aerodynamic resistance to sensible heat and vapor transfer, r_a, is calculated based on wind velocity and surface roughness factors following Williams et al. [29]. The amount of evaporation from the water surface when a rice paddy is flooded is calculated using Sakaguchi's equations [27]:

$$EVAP = V_{evap} + EP \tag{3}$$

$$V_{evap} = \eta\left(1 - \frac{LAI}{LAI_{evap}}\right)E_0 \; if \; LAI \leq LAI_{evap} \tag{4}$$

$$V_{evap} = 0 \; if \; LAI > LAI_{evap} \tag{5}$$

where, V_{evap} is daily evaporation (mm/d), $EVAP$ is daily evapotranspiration (mm/d), LAI is leaf area index, and LAI_{evap} is leaf area index at which evaporation from water surface does not occur. η refers to the coefficient of evaporation from the water surface. The default coefficient value was set at 0.6, which is applied to the reservoir module of the Soil and Water Assessment Tool (SWAT) model [30]. LAI_{evap} was set at 4.0, based on the work of Miyazaki et al. [31], which was modified by Sakaguchi et al. [27].

2.2.2. Puddling Simulation

In East Asian countries including Korea, rice cultivation often starts with transplantation. Most other crop models can only simulate the growth of rice in flooded paddy fields, but are incapable of simulating the environmental effects of paddy managements such as puddling operations on discharge water quality. Puddling is performed prior to transplanting as a part of field preparation, to break clods and to flatten the rice paddy for transplantation. Somura et al. [32] reported that the discharge of pollutants (e.g., soil, nitrogen, and phosphorous) could significantly increase during (or shortly after) a puddling practice in Japan. APEX-Paddy was designed to simulate sediment resuspension with a puddling operation. Sediment concentration in effluent water is calculated using a modified Stokes equation and residual concentration of sediment [33]:

$$C_{sed,f} = (C_{sed,i} - C_{sed,rsd}) \times e^{(-0.184 \cdot t \cdot d_{50})} + C_{sed,rsd} \tag{6}$$

$$d_{50} = e^{(0.41 \cdot F_{clay} + 0.27 \cdot F_{silt} + 0.57 \cdot F_{sand})} \tag{7}$$

where, $C_{sed,f}$ is final soil concentration in the water body (mg/L), $C_{sed,i}$ is soil concentration in the water body during day one of puddling (mg/L), t is time of occurrence (day), and $C_{sed,rsd}$ is concentration of remaining soil in water body (mg/L). d_{50} refers to the diameter of the soil particles (μm), and F_{clay}, F_{silt}, F_{sand}, respectively, refer to the ratios of clay, silt, and sand grain sizes in the surface soil. In conjunction with paddy water balance and nutrient transport modules, discharge of nitrogen and phosphorous can be calculated based on fertilizer management, irrigation schedule, and daily weather conditions.

2.2.3. Transplanting Simulation

While other upland crops are directly seeded on cultivated land, paddy rice is seeded in seedbeds and grows for 25–30 days in a nursery before the seedlings are transplanted into a puddled field. The rice transplanting promotes higher yields and less weeding. The Leaf Area Index (*LAI*), during the emergence and falling of leaves, was calculated using the following equation after Williams et al. [29]:

$$LAI_i = LAI_{0,i} + \Delta HUF_i \times XLAI_i \times \sqrt{REG_i} \times \frac{LAI_{0,i}}{TLAI} \tag{8}$$

$$HUF_i = \frac{HUI_i}{HUI_i + e^{\alpha - \beta \cdot HUI_i}} \tag{9}$$

In Equation (8), $LAI_{0,i}$ and LAI_i are the daily initial *LAI*, and final *LAI*, of a crop (i), respectively, $XLAI_i$ is the maximum *LAI*, *TLAI* is the total *LAI* during a growth period, REG_i is the stress factor of the crop, and ΔHUF_i is the daily amount of change of the heat unit. In Equation (9), HUI_i refers to the heat unit index of the crop, HUF_i refers to the heat unit factor of the crop, and α and β refer to coefficients related to the growth characteristics of the crop. A transplantation operation added to APEX-Paddy was designed to simulate the start of the crop growth with non-zero *LAI*, biomass amount, and controlled the plant population, which otherwise are forced to start from zero at seed-planting in APEX version 1501(APEX1501).

2.3. Model Calibration and Validation

For model calibration, the APEX-auto Calibration and UncerTainty Estimator (APEX-CUTE) programs (3.0 version, Texas A&M AgriLife Research, Temple, TX, USA, https://epicapex.tamu.edu/apex/) were used. APEX-CUTE is a calibration method, which uses a dynamically dimensioned search (DDS) algorithm [34]. The DDS algorithm drives the model by sequentially applying candidate values as input data until the maximum value of the objective function is derived, and then calculates the actual statistics for the model. Random changes are applied to the optimized value to produce another candidate value, which is applied to the model. APEX-CUTE is programmed to repeat the above process for as many times as the testing of the predetermined objective function.

The Nash-Sutcliffe Efficiency (*NSE*) [30], Percent Bias (*PBIAS*), and coefficient of determination (R^2) were used as the objective functions for model calibration. The *NSE* indicates that the means of field data, rather than the simulated values, should be used for more accurate results, when the derived value ranges from 0 to 1.0. The closer the simulated values and field data are, the closer the derived value is to 1.0 [35,36]. The *NSE* was calculated using Equation (10):

$$NSE = 1 - \sum_{i=1}^{n} \left(Y_i^{obs} - Y_i^{sim} \right)^2 / \sum_{i=1}^{n} \left(Y_i^{obs} - Y^{mean} \right)^2 \tag{10}$$

where, Y_i^{obs} and Y_i^{sim} are observed and simulated data at time i, respectively, Y^{mean} is the mean of observed data for the constituent being evaluated, and n is the total number of observations [37]. *PBIAS* evaluates central trends of simulated output by estimating the sum of residuals, the difference in data points between the observed and predicted normalized by the sum of observed data [38]. The optimal value for *PBIAS* is 0, with low-magnitude values indicating accurate model simulation [37]. Positive and negative values indicate model underestimation and overestimation bias, respectively.

$$PBIAS = \sum_{i=1}^{n} \left(Y_i^{obs} - Y_i^{sim} \right) / \sum_{i=1}^{n} Y_i^{obs} \times 100\% \tag{11}$$

Moriasi et al. [37] suggested the criteria for evaluation (Table 2) based on the performance value of the watershed model. The simulation result of the model in this study was evaluated based on these criteria.

Table 2. General performance rating for recommended statistics [37].

Measure	Output Response	Performance Evaluation Criteria			
		Very Good	Good	Satisfactory	Not Satisfactory
R^2	Flow [a]	$R^2 > 0.85$	$0.75 < R^2 \leq 0.85$	$0.60 < R^2 \leq 0.75$	$R^2 \leq 0.60$
	N	$R^2 > 0.80$	$0.60 < R^2 \leq 0.70$	$0.30 < R^2 \leq 0.60$	$R^2 \leq 0.30$
NSE	Flow	$NSE > 0.80$	$0.70 < NSE \leq 0.80$	$0.50 < NSE \leq 0.70$	$NSE \leq 0.50$
	N/P	$NSE > 0.65$	$0.50 < NSE \leq 0.65$	$0.35 < NSE \leq 0.50$	$NSE \leq 0.35$
PBIAS	Flow	$PBIAS \geq \pm 5$	$\pm 5 > PBIAS \geq \pm 10$	$\pm 10 > PBIAS \geq \pm 15$	$PBIAS \geq \pm 15$
	N/P	$PBIAS \geq \pm 10$	$\pm 10 > PBIAS \geq \pm 20$	$\pm 20 > PBIAS \geq \pm 30$	$PBIAS \geq \pm 30$

Note: [a] Includes stream flow, surface runoff, and base flow for watershed-and field-scale models.

3. Results and Discussion

3.1. Characterization of Paddy Rice for APEX Simulation

In the APEX-Paddy model, the *LAI* value of rice at transplanting was estimated based on the growing degree units of seedlings. The estimated *LAI* of 0.1 was then used as the initial value in the APEX simulation as a part of the transplanting operation. Additionally, the heat unit factor of crop (HUF) during the cultivation period was reduced by the amount of heat units accumulated during the nursery period. The growth characteristic curve according to Equations (8) and (9) for transplanted paddy rice was calibrated to field data, as the default coefficient values reflect seed-planted upland rice (Figure 3). When compared to upland rice (default in APEX), paddy rice showed a faster growth rate in early growing season. As depicted in Figure 3, the *LAI* curve for paddy rice diverts from upland rice at 30% of the growing season and establishes the full canopy before reaching 80% of the maturity.

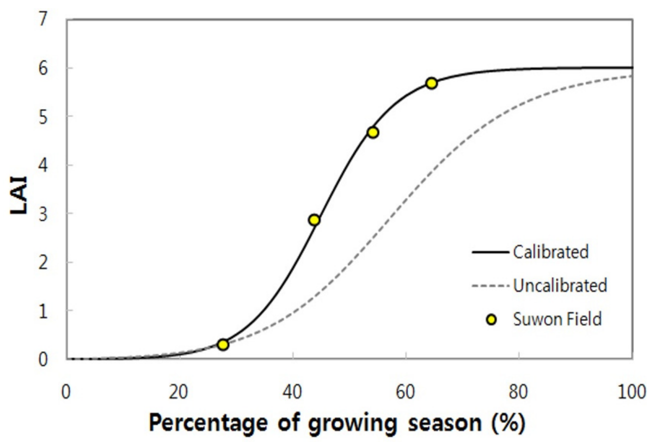

Figure 3. Calibration of the leaf area development curve. *LAI* in the *Y*-axis stands for leaf area index.

The weight of the rice root during the initial cultivating period after transplantation was 35% of the total biomass and the growth of roots almost ceased after the heading season. Consequently, the root weight proportion of the whole plant decreased to 16% through the heading season, and to 7% by the harvesting season. Using these values, the root growth characteristics of paddy rice were refined for the model. The root-shoot weight ratio is calculated using Equation (12):

$$RW_i = DM_i \times [\varepsilon \times (1 - HUI_i) + \gamma \times HUI_i] \quad (12)$$

where, RW_i is the total root weight of the crop (i) (tons/ha), DM_i is the total biomass of the crop (i) (tons/ha), and ε and γ refer to the coefficient of the crop. Important crop parameters for simulating paddy rice compared with upland rice are summarized in Table 3. Detailed descriptions of parameters are in the work of Stenglich and Williams [39].

Table 3. Important crop parameters for simulating paddy rice compared with upland rice.

Parameters	Description	For Upland Rice	For Paddy Rice
DLAP1	First point on optimal leaf area development curve.	30.01	28.01
DLAP2	Second point on optimal leaf area development curve.	70.95	51.95
RWPC1	Fraction of root weight at emergence.	0.40	0.47
RWPC2	Fraction of root weight at maturity.	0.20	0.05
PPLP1	Plant Population for Crops & Grass—1st Point on curve.	125.60	65.30
PPLP2	Plant Population for Crops & Grass—2nd Point on curve.	250.95	130.95

3.2. Effects of Paddy Management on Water and Nitrogen Balance

The Icheon paddy model was calibrated based on daily discharge rates that were measured at the outlet of the paddy field from May to September of 2002. R^2 was used as the main objective function for calibrating the model to extract the optimum parameter value. As depicted in Figure 4, the performance of the paddy model is demonstrated to be excellent in predicting runoff discharge rate during the calibration period ($R^2 = 0.88$, $NSE = 0.87$, $PBIAS = -14.57\%$), which proves that the simulation effectively reflects the field data. The calibrated Icheon site model was evaluated for runoff estimation during the cropping season (June to September) of 2003. The performance statistics indicated good performance ($R^2 = 0.80$, $NSE = 0.65$, $PBIAS = 9.6\%$), which also supports the accurate simulation of field data.

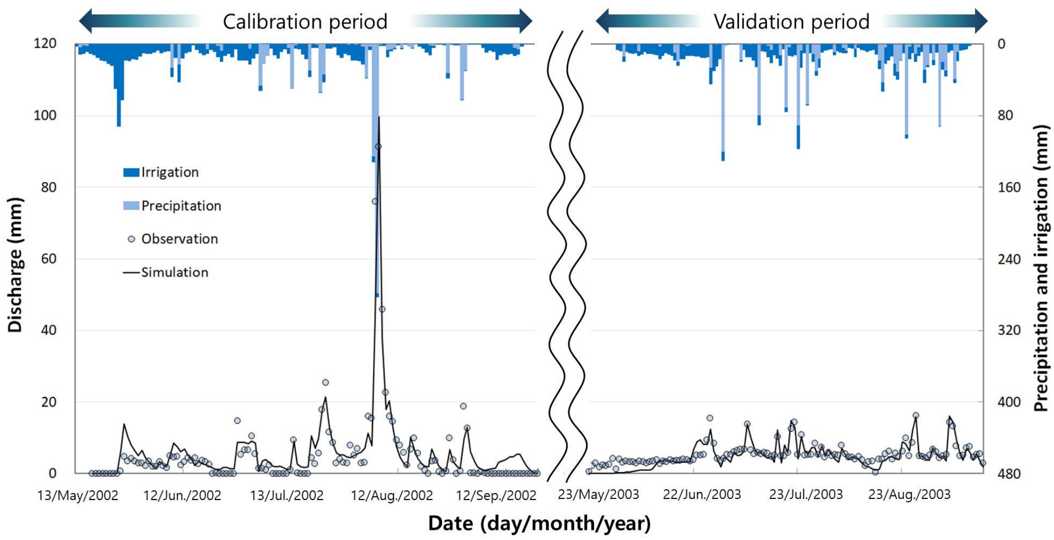

Figure 4. Predicted daily paddy field discharges are calibrated for the growing season in 2002, and then validated for the year 2003 at the Icheon site.

Figure 5 presents the difference between simulated and observed discharge data during the growing season of 2014 at the Gimje site. The APEX-Paddy model effectively simulated runoff events after outlet weirs were removed as a part of the paddy management. For example, the predicted peaks on 24 May 2014, mid-summer drainage on 9 July 2014, and near-harvest on 1 October 2014 are the result of discharge operations in scheduled managements. Moreover, no discharge was predicted after the re-installment of the outlet weir (60 mm high) on 5 August 2014 despite the large storm event on 7 August 2014 (58.6 mm) until mid-month, when ponding water topped the weir and started to overflow ($R^2 = 0.77$, $NSE = 0.70$, $PBIAS = 10.82\%$).

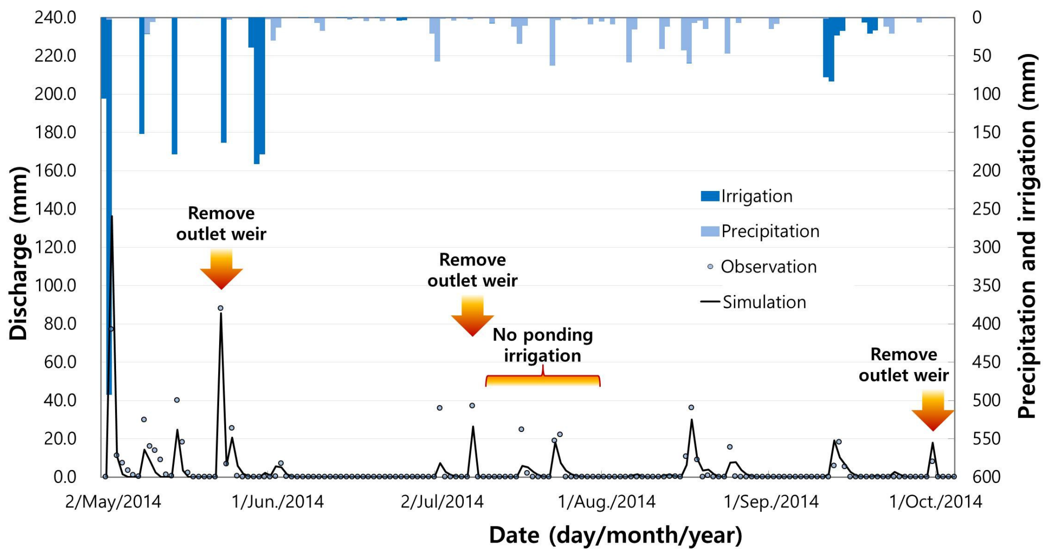

Figure 5. Simulated discharge amounts indicate that the timing and magnitude of peak discharges in response to outlet weir management are well predicted during the growing season in 2014 at the Gimje site.

Nitrogen (N) fertilizer is the main source of nitrogen yield in paddy discharge water. As summarized in Table 1, typically a total of 100–120 kg N/ha of fertilizer is applied during a growing season. As the N fertilizer is applied in mineral form, poorly managed paddy irrigation and discharge can make significant contribution to QN loads in the downstream of paddy fields. Only the Icheon site was monitored for QN during 2002 and 2003 and data was available for model evaluation. At the monitoring site, the two important factors that affect QN were the runoff discharge rate and the timing of fertilizer application. As depicted in Figure 6, the largest discharge event in 2002 resulted in the greatest daily QN for the year. Furthermore, the hikes of QN were often initiated by fertilizer applications. In general, the model calibrated for runoff discharge successfully simulated the timing and peak rates of QN when compared to observed values (R^2 = 0.66, *NSE* = 0.63, *PBIAS* = 2.1%). In the validation year (2003), the performance statistics for QN were measured well beyond acceptable ranges (R^2 = 0.64, *NSE* = 0.43, *PBIAS* = 4.5%). The predicted values satisfy the criteria in evaluating the model's performance recommended by Moriasi et al. [37].

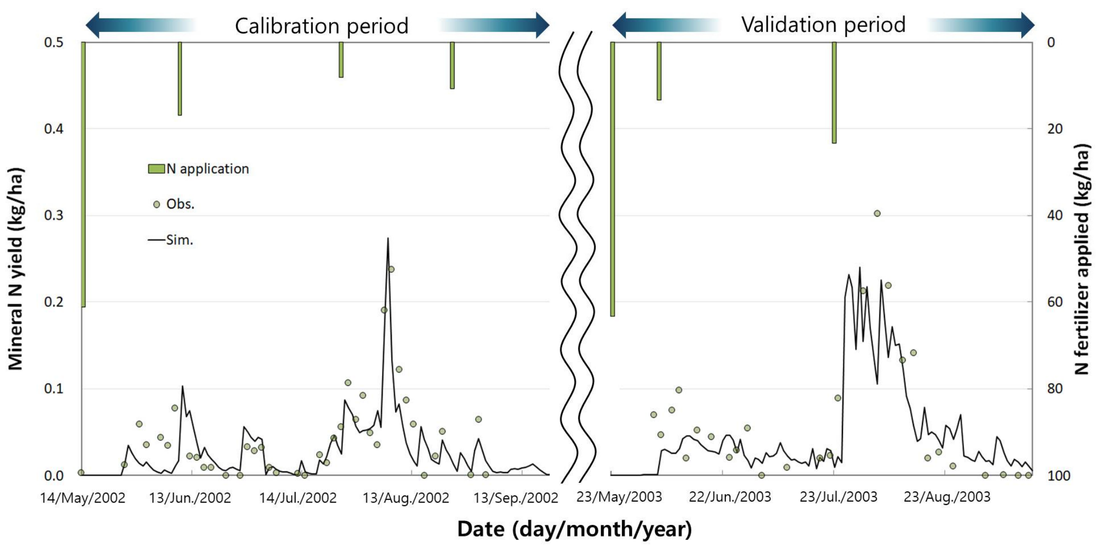

Figure 6. Daily QN predicted by APEX-Paddy is calibrated for the growing season in 2002 and then validated in 2003 at the Icheon site.

3.3. Performance of APEX-Paddy over APEX1501

A prevailing advantage of the proposed APEX-Paddy algorithm for simulating hydrological processes over the conventional SCS-CN method [22] is the improved simulation of water management and of related hydrologic processes calculation specific to paddy environment. As accurate prediction of water balance is essential to estimating water quality variables such as sediment yield and nutrient yield, the improved water balance estimation provides a synergetic effect in predicting water quality output.

For comparison, a baseline simulation was conducted for the Icheon field, in which runoff was estimated using the SCS-CN method (APEX1501) and was compared with the APEX-Paddy. The uncalibrated Icheon dataset was rerun by APEX1501 model and calibrated for runoff and QN using the APEX-CUTE program [40]. A total of 10,000 iterations were made using the DDS algorithm to calibrate 30 APEX parameters. Outputs from both APEX-Paddy and APEX1501 were collected and compared for relative performance estimation. Results indicate that APEX1501 significantly overestimates peak rates of runoff and QN.

The best result of the SCS-CN method predicted the biggest runoff event in July 2002, which was greater than observed runoff rate by twice the magnitude. Table 4 presents the model calibration and validation results related to daily runoff. Overall the simulated runoff by APEX1501 was unsatisfactory as evidenced by performance statistics: $R^2 = 0.57$, $NSE = -1.91$, $PBIAS = -80.9\%$. The negative *NSE* value indicates that there exists a notable difference between simulated runoff and the mean observed value while the predicted runoff has meaningful correlation with observed data. In particular, the largest storm event in August 2002 was highly overestimated for peak discharge estimation with the APEX1501 estimation because the paddy defined with the model had no outlet control and therefore had zero surface storage capacity to retain the stormwater (see Figure 7). The high peak discharge estimation is well reflected in the APEX1501 output on other small to intermediate storm events. The negative *PBIAS* value implies that predicted runoff was highly overestimated. According to Moriasi et al. [37], the performance of the APEX1501 is unsatisfactory.

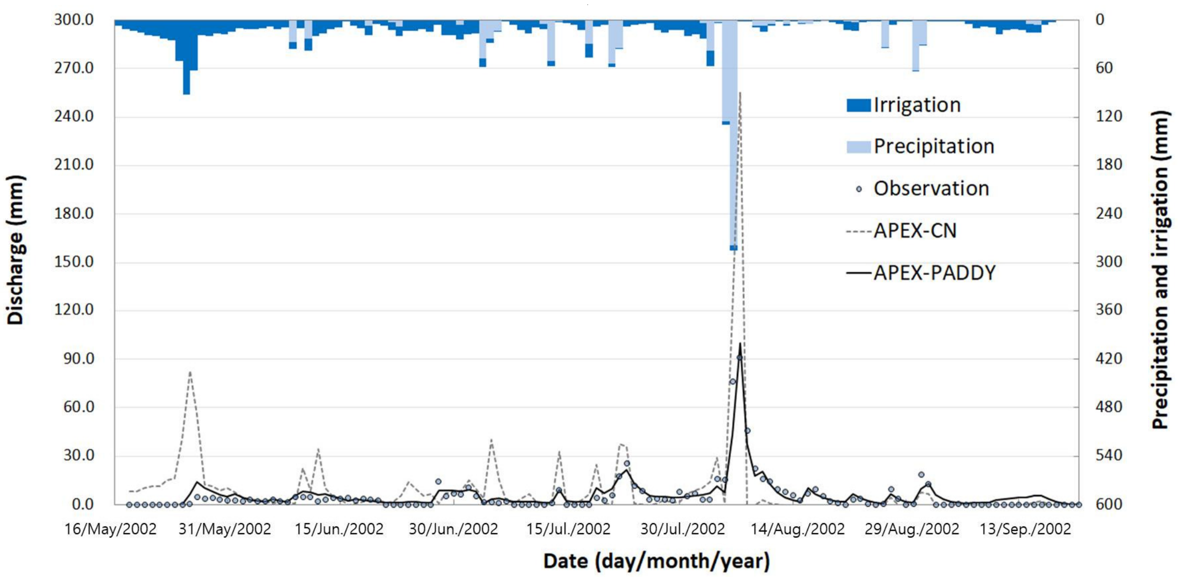

Figure 7. Predicted daily discharge hydrographs indicate that APEX-Paddy successfully simulates high peaks in daily discharge at the Icheon site by allowing surface retention of stormwater. The APEX1501 model with the SCS-CN method over-predicted peak daily discharges up to 250% of the measured value.

Table 4. Summary of calibration and validation results for daily discharge at the study site.

Item	Location	Period	No. of Measure (Day)	Rainfall (mm)	Irrigation (mm)	Discharge (mm)		R^2	*NSE*	*PBIAS* (%)
						Obs.	Sim.			
APEX1501										
Calibration	Icheon	2002	127	882.0	1291.8	670.4	1222.0	0.57	−1.91 (not satisfactory)	−80.9 (not satisfactory)
APEX-PADDY										
Calibration	Icheon	2002	127	882.0	1291.8	670.4	733.8	0.88 (very good)	0.87 (very good)	−14.6 (satisfactory)
Validation	Icheon	2003	86	984.7	893.1	539.4	526.4	0.80 (good)	0.65 (satisfactory)	9.6 (good)
	Gimje	2014	156	737.8	887.0	606.8	568.8	0.77 (good)	0.70 (good)	10.8 (satisfactory)

Table 5 presents the test results for daily QN discharge. At the Icheon site, the APEX1501 predicted the QN yield of 2.68 kg/ha during the monitoring period in discharge water with the peak of 1.21 kg/ha in 2002, while the APEX-Paddy estimated only 1.39 kg/ha during the monitoring period with the peak rate of 0.18 kg/ha. The APEX-Paddy result compares well with observed QN (1.76 kg/ha) and peak rate (0.24 kg/ha) in 2002. The estimated N yield by APEX-Paddy compares well with APEX1501 regarding how APEX-Paddy improves the calculation of nutrient yield because of the improvement in water discharge calculation.

Table 5. Dissolved nitrogen loads in paddy discharge (QN) estimated by Paddy module compared with the SCS-CN method at the Icheon site.

Class	Year	#Measures	Total Load [a] (kg/ha)	Peak Load (kg/ha)	R^2	*NSE*	*PBIAS* (%)
APEX1501	2002	39	2.68	1.21	0.02	−14.4	−52.9
APEX-Paddy	2002	39	1.39	0.18	0.66	0.68	2.1
	2003	27	1.17	0.22	0.64	0.43	4.5
Observed	2002	39	1.76	0.24			
	2003	27	1.31	0.30			

Note: [a] Sum of mineral nitrogen yield at the measured date.

In reality, even a best management practice (BMP) for controlling the Non-Point Sources (NPS) pollution may not be effective if the BMP results in meaningful a decrease in crop yield. This means that recommendations on controlling NPS pollution must be developed in a way that minimizes influencing crop production and promotes economic sustainability for farmers. Table 6 presents simulated and statistical data (1996–2014) of rice production at the Icheon and the Gimje site [41]. The predicted rice yield by APEX-Paddy compares well with observed values (*PBIAS* = 4.0%) for the Icheon field. Similarly, APEX-Paddy performed well for the Gimje field in predicting rice yield (*PBIAS* = 0.75%), which is in part attributable to the successful improvement in crop parameterization for root growth and *LAI* development conducted as part of the modeling study.

Table 6. Estimated yield of rice at the study sites (APEX-Paddy).

Location	Observed Rice Yield (ton/ha)		Estimated Rice Yield (ton/ha)		*PBIAS*
	Average	St. Dev.	Average	St. Dev.	
Icheon	6.53	0.32	6.27	0.43	4.02%
Gimje	7.19	0.34	7.13	0.60	0.75%

4. Conclusions

With agricultural management including fertilizer application and irrigation, paddy fields are potentially a source of non-point pollution. This study found that agricultural management significantly influences the discharge water quality of rice paddy fields. The ability to simulate paddy management processes using physically based algorithms had to be incorporated to the APEX model to successfully calibrate flow and nitrogen yield. The Agricultural Policy/Environmental eXtender model was modified for simulating biophysical processes in paddy fields under flooded (and dry) conditions. Agricultural management for growing rice was prescribed in scheduled operations, and relevant biophysical processes were constructed in a paddy algorithm.

The ability to assess the effects of paddy management on water quantity and quality in simulation models allows for a better understanding of the interactive processes of management, water, and pollutant loads. Fertilizer management can also improve discharge water quality while maintaining rice production. Two experimental paddy fields, Icheon and Gimje in Korea, were selected for evaluating the paddy module in the APEX model. As demonstrated in the case study at the two paddy fields in Korea, incorporating physical processes of paddy management into APEX resulted in substantial improvement in predicting water balance and nitrogen yield. Refined characterization of paddy rice growth might have improved water quality output as well as rice yield prediction. However, nutrient dynamics may need further improvement to better represent microbial effects in standing water and in the anoxic zone of the subsoil layers.

In Korea, paddies are often located in the vicinity of large waterbodies such as rivers or lakes, in order to meet the substantial irrigation demand. Intense agricultural management of paddy rice including fertilizer and other chemical applications has been identified as possible sources of water pollution. The generally short travel time for paddy discharge to receiving a waterbody could cause significant water quality impacts during cultivation because of puddling, transplanting, and other scheduled management practices. These environmental effects can be amplified in places where paddies are predominant land uses because it is common that such scheduled paddy managements are near-concurrently operated. The proposed APEX-Paddy model showed a significant improvement in predicting the environmental processes over the SCS-CN method. Though beyond the scope of this paper, the ultimate goal of the model development is to build a reliable simulation tool for developing innovative conservation practices for agricultural NPS pollution that can account for local climate condition, soil properties, and agricultural management specifics. As a follow-up, APEX-Paddy will continue to be applied to demonstrate the effectiveness of BMPs implementation for paddy discharge water in Korea at the national scale, and the findings will be incorporated in developing agricultural policies.

Acknowledgments: This study was carried out with the support of the "Research Program for Agricultural Science & Technology Development (Project No. PJ010890)", National Institute of Agricultural Science, Rural Development Administration, Korea.

Author Contributions: Min-Kyeong Kim conceived and designed APEX-Paddy model; Jaehak Jeong build the model; Soon-Kun Choi and Jaehak Jeong analyzed the data; Soon-Kun Choi, Jaehak Jeong and Min-Kyeong Kim wrote the paper.

Conflicts of Interest: The authors declare no conflict of interest.

References

1. Kang, M.S.; Park, S.W.; Lee, J.J.; Yoo, K.H. Applying SWAT for TMDL programs to a small watershed containing rice paddy fields. *Agric. Water Manag.* **2006**, *79*, 72–92. [CrossRef]
2. Ministry of Agriculture, Food and Rural Affairs (MARFA). *The 2013 Agriculture, Forestry and Fishery Survey*; Ministry of Agriculture, Food and Rural Affairs: Sejong-si, Korea, 2013.
3. Maclean, J.; Hardy, B.; Hettel, G. *Rice Almanac*, 4th ed.; International Rice Research Institute: Los Banos, Philippines, 2013.
4. Jeon, J.H.; Yoon, C.G.; Jung, K.W.; Jang, J.H. HSPF-Paddy simulation of water flow and quality for the Saemangeum watershed in Korea. *Water Sci. Technol.* **2007**, *56*, 123–130. [CrossRef] [PubMed]
5. Song, I.; Song, J.H.; Ryu, J.H.; Kim, K.; Jang, J.R.; Kang, M.S. Long-term evaluation of the BMPs scenarios in reducing nutrient surface loads from paddy rice cultivation in Korea using the CREAMS-PADDY model. *Paddy Water Environ.* **2017**, *15*, 59–69. [CrossRef]
6. Kawara, O.; Hirayma, K.; Kunimatsu, T. A study on pollutant loads from the forest and rice paddy fields. *Water Sci. Technol.* **1996**, *33*, 159–165. [CrossRef]
7. Zhou, Q.; Zhu, Y. Potential pollution and recommended critical levels of phosphorus in paddy soils of the southern Lake Tai area, China. *Geoderma* **2003**, *115*, 45–54. [CrossRef]
8. Matsuno, Y.; Nakamura, K.; Masumoto, T.; Matsui, H.; Kato, T.; Sato, Y. Prospects for multifunctionality of paddy rice cultivation in Japan and other countries in monsoon Asia. *Paddy Water Environ.* **2006**, *4*, 189–197. [CrossRef]
9. Tang, L.; Zhu, Y.; Hannaway, D.; Meng, Y.; Liu, L.; Chen, L. A rice growth and productivity model. *NJAS Wagening. J. Life Sci.* **2009**, *57*, 83–92. [CrossRef]
10. Ahmad, S.; Ahmad, A.; Soler, C.; Ali, H.; Zia-Ul-Haq, M.; Anothai, J. Application of the CSM-CERES-Rice model for evaluation of plant density and nitrogen management of fine transplanted rice for an irrigated semiarid environment. *Precis. Agric.* **2012**, *13*, 200–218. [CrossRef]

11. Inao, K.; Watanabe, H.; Karpouzas, D.G.; Capri, E. Simulation models of pesticide fate and transport in paddy environment for ecological risk assessment and management. *Jpn. Agric. Res. Q.* **2008**, *42*, 13–21. [CrossRef]
12. La, N.; Lamers, M.; Nguyen, V.V.; Streck, T. Modeling the fate of pesticides in paddy rice-fish pond farming systems in northern VieQNam. *Pest Manag. Sci.* **2014**, *70*, 70–79. [CrossRef] [PubMed]
13. Luo, Y.; Spurlock, F.; Gill, S.; Goh, K.S. Modeling complexity in simulating pesticide fate in a rice paddies. *Water Sci. Technol.* **2012**, *53*, 253–261. [CrossRef] [PubMed]
14. Inao, K.; Hojyo, T.; Annoh, H.; Miyazaki, S.; Saito, T.; Parka, H.D. Predicting the behavior of paddy pesticides in a river basin using a simulation model (PADDY-Large): Application to a tributary of the Chikuma River under rice cultivation. *Pestic. Sci.* **2011**, *36*, 413–427. [CrossRef]
15. Tsuchiya, R.; Kato, T.; Jeong, J. SWAT model improvement for discharge process in rice paddies. In Proceedings of the PAWEES-INWEPF Joint International Conference, Kuala Lumpur, Malaysia, 19–21 August 2015.
16. Williams, J.R.; Izaurralde, R.C. *The APEX Model*; BRC Report No. 2005-02; Texas Agricultural Experiment Station, Texas Agricultural Extension Service, Texas A&M University: Temple, TX, USA, 2005.
17. Borah, D.K.; Yagow, G.; Saleh, A.; Barnes, P.L.; Rosenthal, W.; Krug, E.C.; Hauck, L.M. Sediment and nutrient modeling for TMDL development and implementation. Trans. *ASABE* **2006**, *49*, 967–986. [CrossRef]
18. Kim, M.K.; Roh, K.A.; Lee, N.J.; Seo, M.C.; Koh, M.H. Nutrient load balance in large-scale paddy fields during rice cultivation. *Korean J. Soil Sci. Fertil.* **2005**, *38*, 164–171.
19. Kim, M.Y.; Seo, M.C.; Kim, M.K. Linking hydro-meteorological factors to the assessment of nutrient loadings to streams from large-plotted paddy rice fields. *Agric. Water Manag.* **2007**, *87*, 223–228. [CrossRef]
20. Williams, J.R.; Izaurralde, R.C. The APEX model. In *Watershed Models*; Singh, V.P., Frevert, D.K., Eds.; CRC Press, Taylor & Francis: Boca Raton, FL, USA, 2006; pp. 437–482.
21. Rural Development Administration (RDA). *Crop Test Report*; Rural Development Adiministration: Wanju-gun, Korea, 2002; p. 11.
22. Mockus, V. *National Engineering Handbook Section 4, Hydrology*; United States Department of Agriculture (USDA), Soil Conservation Service: Washington, DC, USA, 1972.
23. Wischmeier, W.H.; Smith, D.D. *Predicting Rainfall Erosion Losses, a Guide to Conservation Planning*; Agriculture Handbook No. 537; U.S. Deptment Agriculture, U.S. Government Printing Office: Washington, DC, USA, 1978.
24. Vu, S.H.; Watanabe, H.; Takagi, K. Application of FAO-56 for evaluating evapotranspiration in simulation of pollutant runoff from paddy rice field in Japan. *Agric. Water Manag.* **2005**, *76*, 195–210. [CrossRef]
25. Monteith, J.L. Evaporation and environment. *Symp. Soc. Exp. Biol.* **1965**, *19*, 205–234. [PubMed]
26. Stockle, C.O.; Williams, J.R.; Rosenberg, N.J.; Jones, C.A. A method for estimating the direct and climate effects of rising atmospheric carbon dioxide on growth and yield of crops: Part I-Modification of the EPIC model for climate change analysis. *Agric. Syst.* **1992**, *38*, 225–238. [CrossRef]
27. Sakaguchi, A.; Eguchi, S.; Kato, T.; Kasuya, M.; Ono, K.; Miyata, A.; Tase, N. Development and evaluation of a paddy module for improving hydrological simulation in SWAT. *Agric. Water Manag.* **2014**, *137*, 116–122. [CrossRef]
28. Jensen, M.E.; Burman, R.D.; Allen, R.G. *Evapotranspiration and Irrigation Water Requirements*; ASCE Manuals and Reports on Engineering Practice No. 70; American Society of Civil Engineers (ASCE): New York, NY, USA, 1990.
29. Williams, J.R.; Izaurralde, R.C.; Steglich, E.M. *Agricultural Policy/Environmental Extender Model: Theoretical Documentation Version 0806*; BRC Report No. 2008-17; Texas Agricultural Experiment Station, Texas Agricultural Extension Service, Texas A&M University: Temple, TX, USA, 2008.
30. Nash, J.E.; Sutcliffe, J.V. River flow forecasting through conceptual models; part I—A discussion of principles. *J. Hydrol.* **1970**, *10*, 282–290. [CrossRef]
31. Miyazaki, N.; Kamewada, K.; Iwasaki, S. Quality changes of agricultural water passing through paddy fields. *Bull. Tochigi Prefect. Agric. Exp. Stn.* **2005**, *55*, 45–55.
32. Somura, H.; Takeda, I.; Mori, Y. Influence of puddling procedures on the quality of rice paddy drainage water. *Agric. Water Manag.* **2009**, *96*, 1052–1058. [CrossRef]
33. Neitsch, S.L.; Arnold, J.G.; Kiniry, J.R.; Williams, J.R. *Soil and Water Assessment Tool Theoretical Documentation Version 2009*; Texas Water Resources Institute Technical Report No. 406; Texas Water Resources Institute, Texas A&M University: Temple, TX, USA, 2011.

34. Tolson, B.A.; Shoemaker, C.A. Dynamically dimensioned search algorithm for computationally efficient watershed model calibration. *Water Resour. Res.* **2007**, *43*, W01413. [CrossRef]
35. Kang, M.S.; Park, S.W. Development and application of total maximum daily loads simulation system using nonpoint source pollution model. *J. Korea Water Resour. Assoc.* **2003**, *36*, 117–128. [CrossRef]
36. Santhi, C.; Arnold, J.G.; Williams, J.R.; Hauck, L.M.; Dugas, W.A. Application of a watershed model to evaluate management effects on point and nonpoint source polution. *Trans. ASAE* **2001**, *43*, 1431–1439. [CrossRef]
37. Moriasi, D.N.; Gitau, M.W.; Pai, N.; Daggupati, P. Hydrologic and water quality models: Performance measures and evaluation criteria. *Trans. ASABE* **2015**, *58*, 1763–1785. [CrossRef]
38. Gupta, H.V.; Sorooshian, S.; Yapo, P.O. Status of automatic calibration for hydrologic models: Comparison with multilevel expert calibration. *J. Hydrol. Eng.* **1999**, *4*, 135–143. [CrossRef]
39. Steglich, E.M.; Williams, J.W. *Agricultural Policy and Environmental Extender Model User's Manual Version 0604*; BRC Report No. 2008-16; Texas Agricultural Experiment Station, Texas Agricultural Extension Service, Texas A&M University: Temple, TX, USA, 2008.
40. Wang, X.; Jeong, J. *APEX-CUTE 4 User Manual*; Texas A&M AgriLife Research, Blackland Research and Extension Center, Texas A&M University: Temple, TX, USA, 2016.
41. Statstics Korea. Available online: http://www.kostat.go.kr/ (accessed on 12 February 2016).

© 2017 by the authors. Licensee MDPI, Basel, Switzerland. This article is an open access article distributed under the terms and conditions of the Creative Commons Attribution (CC BY) license (http://creativecommons.org/licenses/by/4.0/).